Accelerated Insertion of Materials

Manufacturing and Producibility of Hat Stiffened Structure

49th International Society for the Advancement of Material and Process Engineering Symposium and Exhibition

17 May 2004

Pete E. George
pete.e.george@boeing.com

Keith. Rupel
keith.rupel@boeing.com

John Griffith
john.m.griffith@boeing.com

Jointly accomplished by BOEING and the U.S. Government under the guidance of NAVAIR.

Sponsored by DARPA/DSO and administered by NAVAIR through TIA N00421-01-3-0098

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
2004	**N/A**	**-**

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Manufacturing and Producibility of Hat Stiffened Structure	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **The Boeing Company**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**UU**	**29**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Accelerated Insertion of Materials –
Manufacturing and Producibility of Hat Stiffened Structure

- **Background and Problem Definition**
- **Hat Stiffened Panel Processing and Past Challenges**
- **Problem Solution Approach - AIM-C Methodology**
- **Materials Characterization**
- **AIM-C Producibility Heuristics**
- **Hat Structure Definition**
- **Tooling and Processing Approach**
- **First Round Results**
- **Second Round Results**
- **Summary**

- **Background and Problem Definition**
  - **Hat Stiffened structure offers significant structural and fabrication advantages**

  However…….

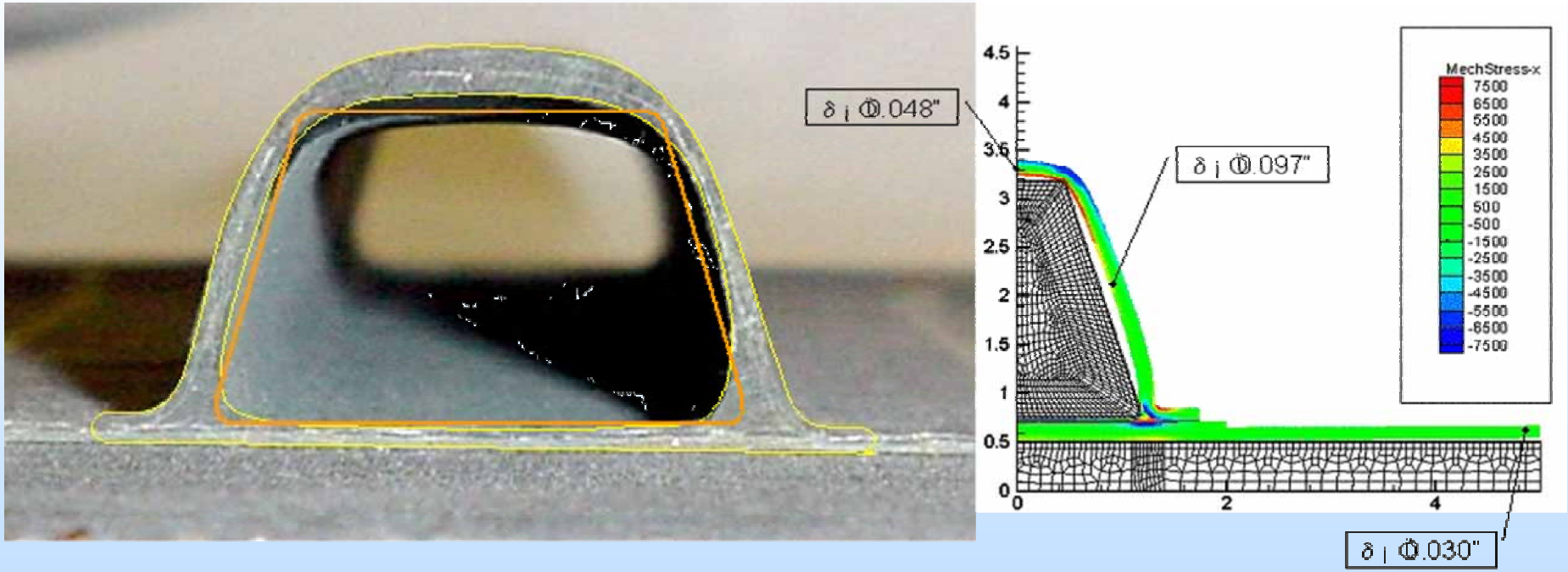
  - **Process development and fabrication of composite hat stiffened structure has proven problematic in the past**
    - **Trial and error without good knowledge of process bounds**
    - **Subsequent quality issues in production**

- Accelerate the process development of hat stiffened structure using AIM-C
- Successfully fabricate quality structure with as few iterations as possible

Hat Stiffened Panel Processing and Past Challenges

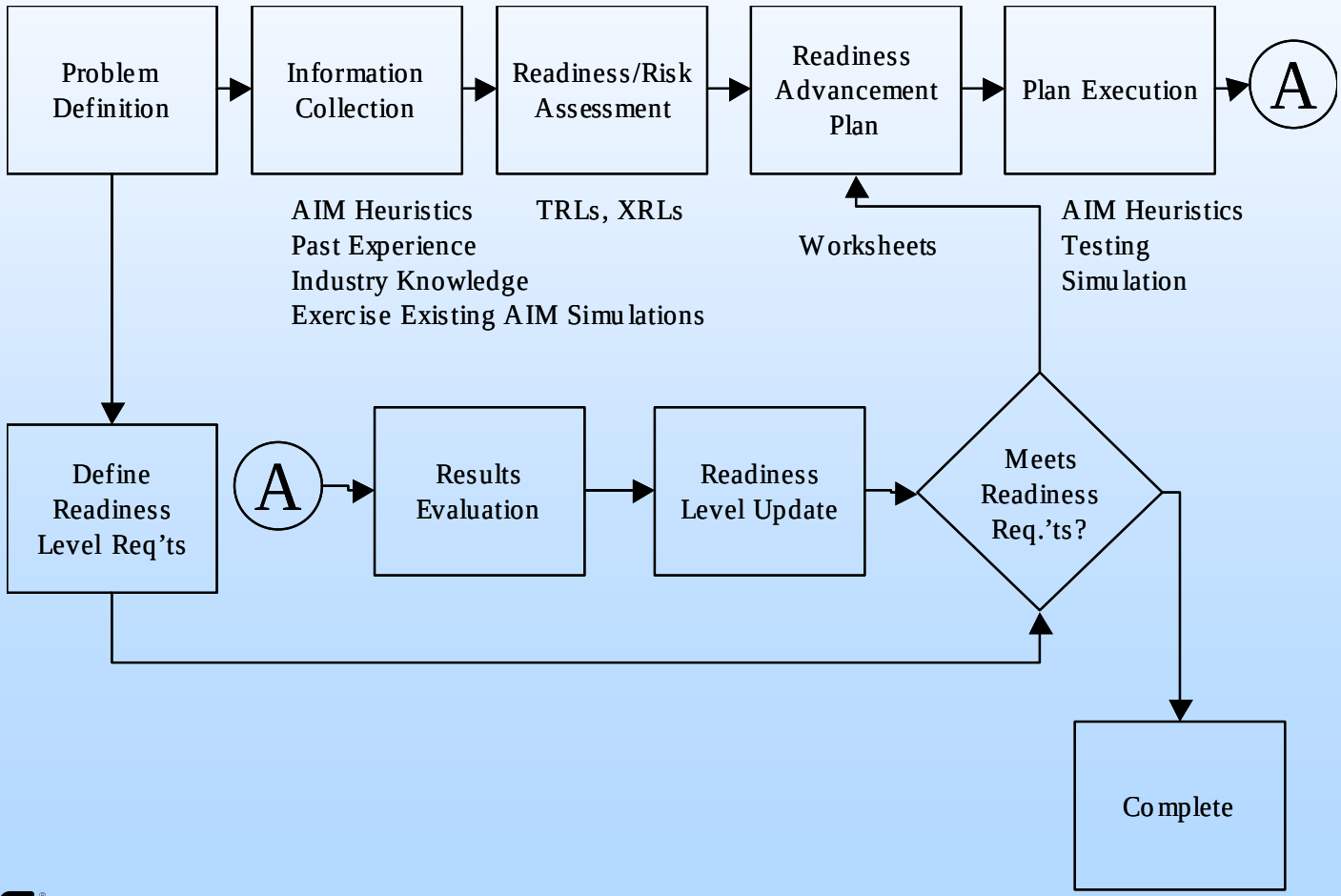
- Hat side wall/cap ballooning where the sidewalls are not flat
- Upper and lower radius thin-out (fiber movement and resin starvation)
- Hat miss-location (hat to hat spacing)
- Curved or snaking stiffener shape
- Stiffener sink where the skin under the stiffener is of less thickness than blueprint
- Other skin thickness variations between under the hat and adjacent to the hat (resin rich or resin poor areas)
- Adhesive migration if adhesive is used in the fillet area.
- Ply waviness around the radii
- Fillet porosity (hat to skin intersection)
- Skin out-of-plane waviness at the stiffener flange edges
- Resin rich areas at the stiffener termination if a net molded stiffener is used
- Trimming errors if the stiffener termination is trimmed after molding
- The typical array of flat panel manufacturing defects including porosity and delaminations

• Hat Stiffened Panel Processing and Past Challenges

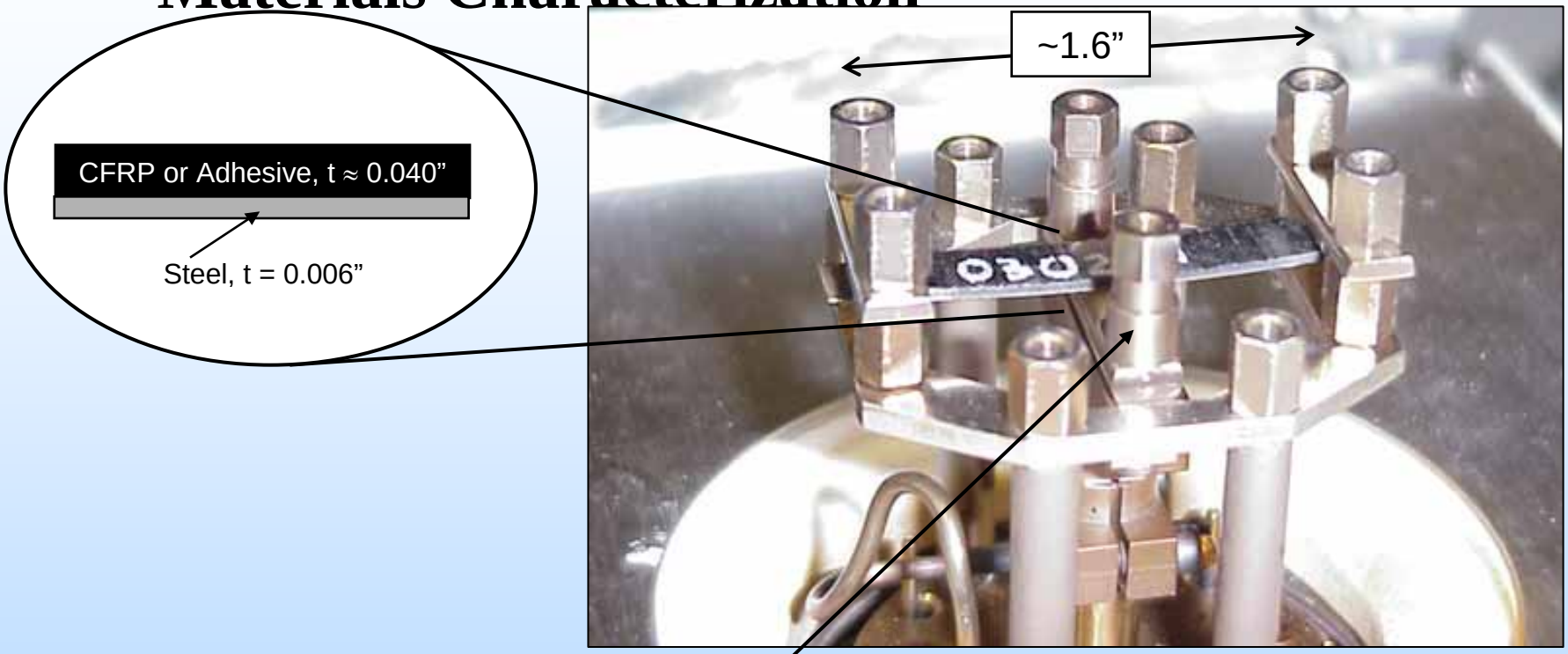


- Ballooning
- Lower radius thickening
- Upper radius thinning
- "Bow waves"
- Radius waviness
- Radius porosity

• AIM-C Methodology



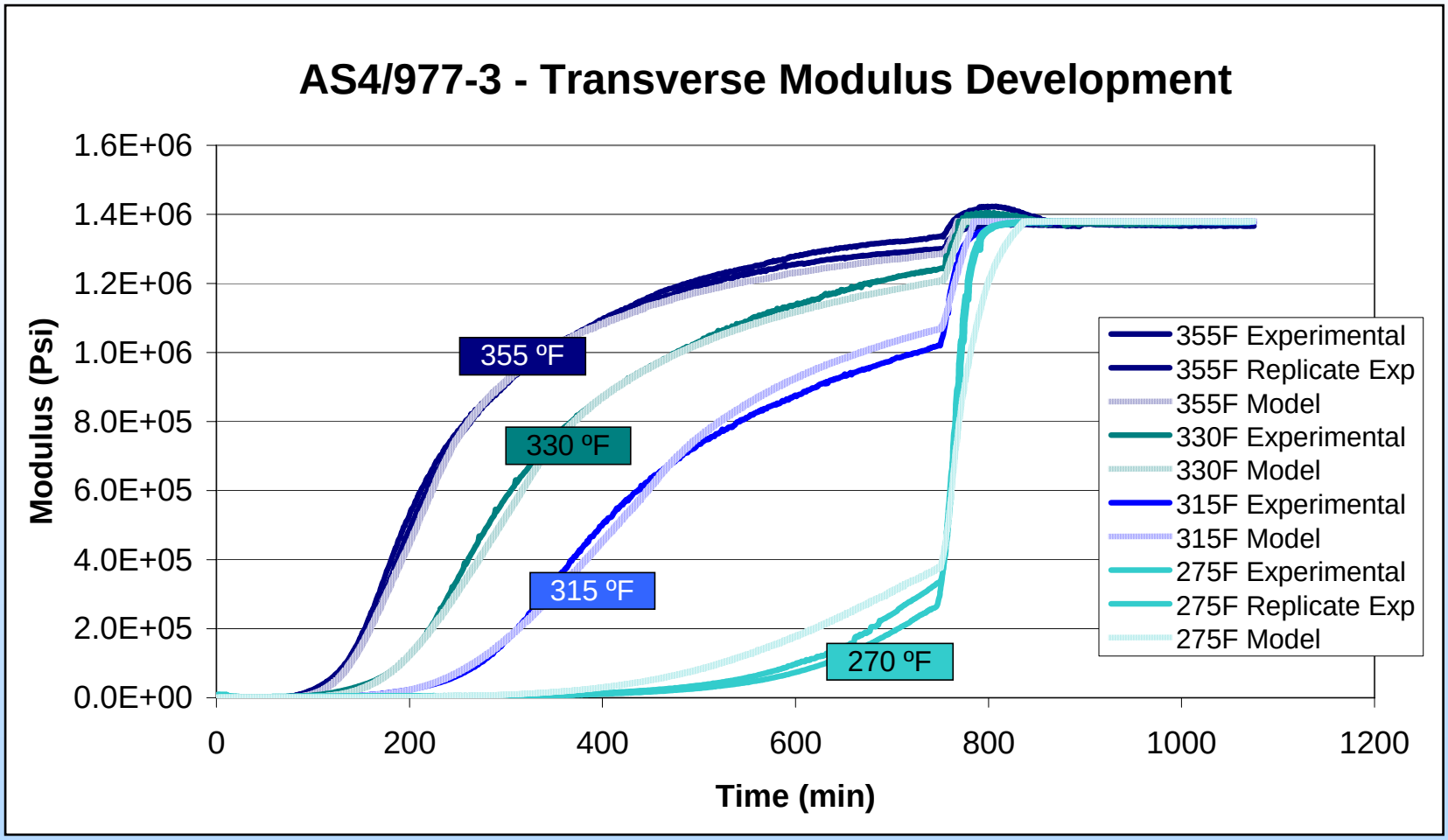
• Materials Characterization



Dynamically oscillate (Dynamic Test) crosshead to measure modulus or apply constant force (Creep Test) and measure beam displacement due to cure shrinkage and CTE

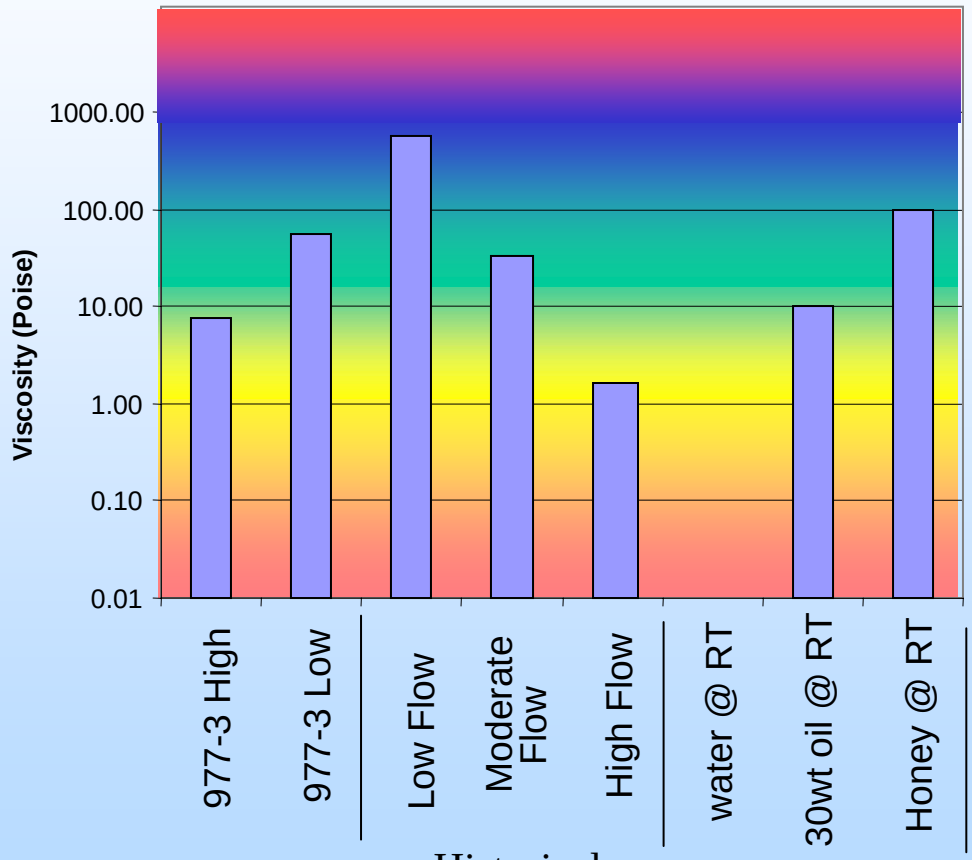
Supporting the curing material with the steel shim eliminates the need for staging of DMA specimens meaning Accelerated Material Testing

- **Materials Characterization**



• Materials Characterization

Minimum Viscosity Assessment



! Consolidation Challenges Due to High Viscosity

Autoclave Bagging Technique A

Autoclave Bagging Technique B

Autoclave Bagging Technique C

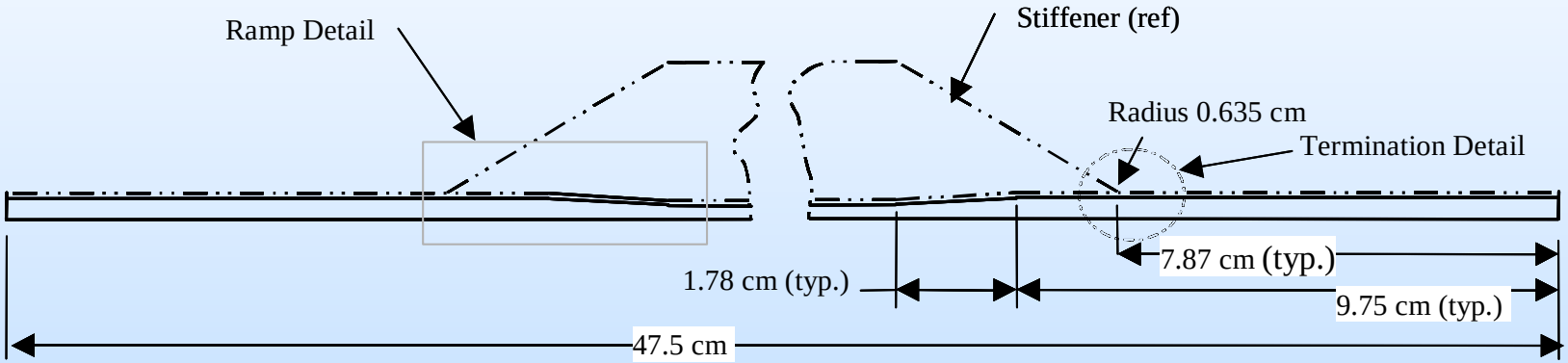
!

Use Bagging Method B

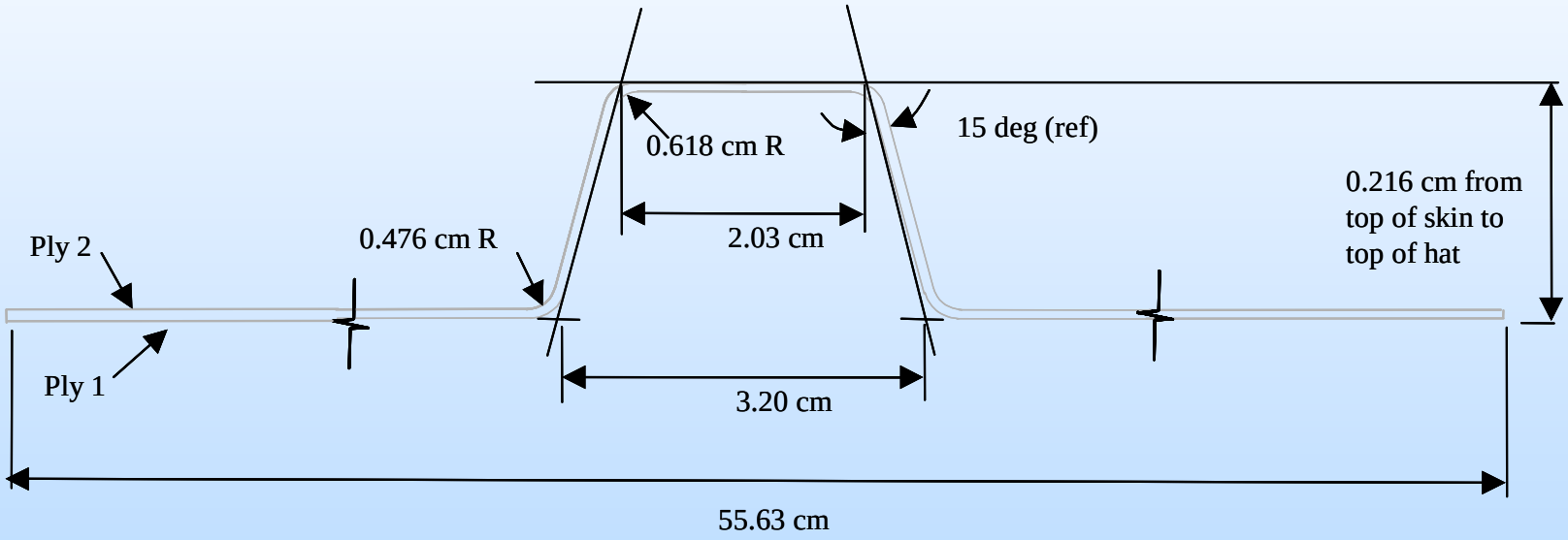
• AIM-C Producibility Heuristics

Issue	Semi-Rigid Cocure Tooling	Cobond with Wet Hats
Thick/Thin Flanges	Flange thickness is a minor problem assuming semi-rigid section extends into bay between stiffeners. (<10% flange thickness error). Assume flange and skin under flange experience the same fiber volume change.	Flange edge thickness more variable. Flanges typically 15% thin due to tooling pressure. (Fiber volume change in flanges and skins under the flanges. Resin flowed out toward midbay and noodle area.)
Skin Waviness Beyond the Hat	Typically not a significant issue. A slight (<5%) thickness increase may be noted beyond stiffener flange.	Not an issue with precured skins
Shim Induced delamination at hat termination	Tooling is rigid enough to be pinned in place and prevent undercut by the shim. Some slight flange fiber movement over the shim is possible but can be trimmed back to the required shape	No shim required.
High/Low fiber volume at flange termination	Low fiber volume is common in net formed hats for ply pull back. Tooling approach does not significantly affect this.	Low fiber volume is common in net formed hats for ply pull back. Tooling approach does not significantly affect this.
End of hat thick or thin flanges	Limited intensifier droop near the end of the panel (5%)	Tooling flexibility will allow a roll-off or pinching at the hat termination. Expect the flanges to taper to 15% thin at tooling termination. If the hats are not net shape, this in not much of an issue.
Skin Waviness beyond the hat	The hat mandrel can create markoff beyond the end of the hat. Since this is typically a mating surface, shims are used to reduce this effect. Expect a 10% thickness decrease with shims.	Not an issue with precured skins
Tool mark-off	Tool mark off can be reduced by terminating the inner stiffening member before the flexible coatings.	Not an issue with precured skins

- **Hat Structure Definition**



- **Hat Structure Definition**



- **Tooling and Processing Approach**

Studies with AIM Structures Tools indicated significant performance knockdowns if out of plane wrinkles occurred at hat termination.

AIM producibility heuristics indicated this could be an issue for co-cure structure

No heat-up rate or exotherm issues for any of the proposed tooling configurations based on simulation.

Co-bonding was selected over co-curing

- **First Round Results – Simulation configuration**

Cure Cycle Information

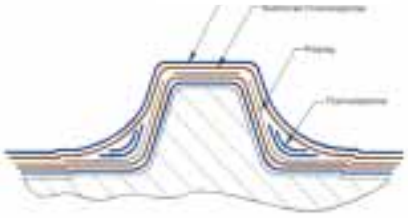
Pre Processor 1
HSP Geometry, Lay-up & Tooling Configuration

PATRAN

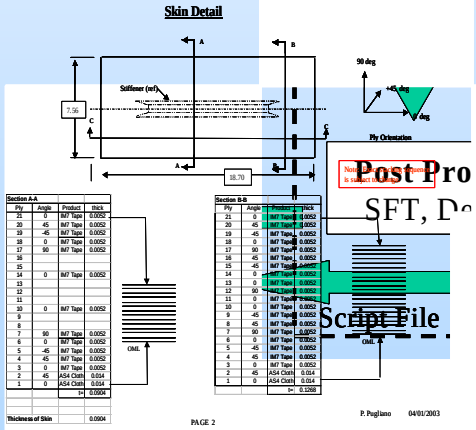
Pre Processor 2
Autoclave, Cure Cycle, Material Selection & Caul Plate Configuration

Tooling Configuration

Geometry & Lay-up from Structures



Tooling Configuration

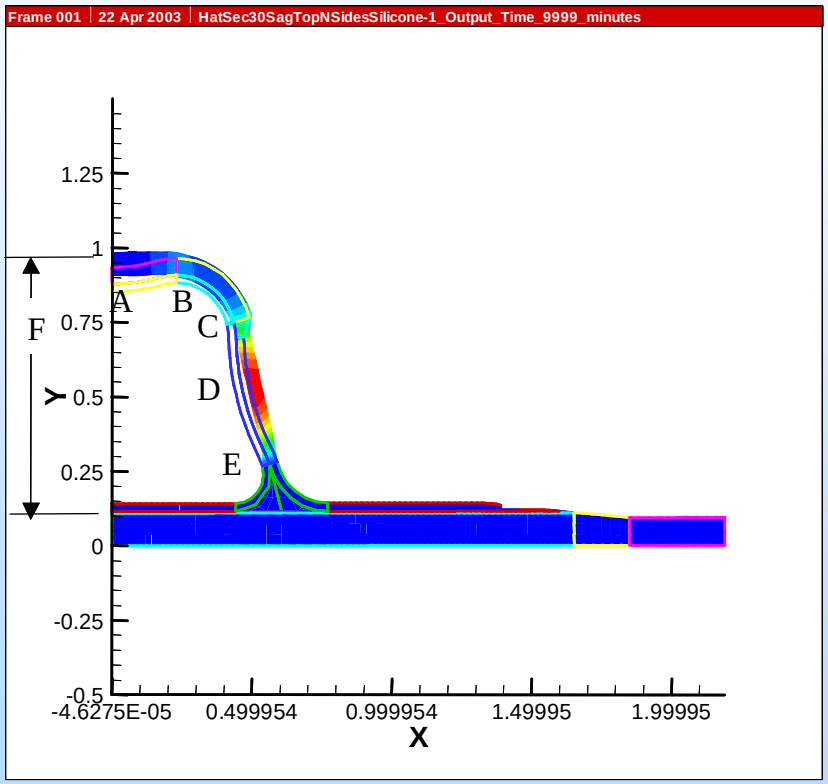


Processing Module
Using Resin, Fiber & Lamina

Detailed Data Output vs. Time

Structures information

- **First Round Results – Simulation Shape Prediction**



-

Predicted Mandrel Growth

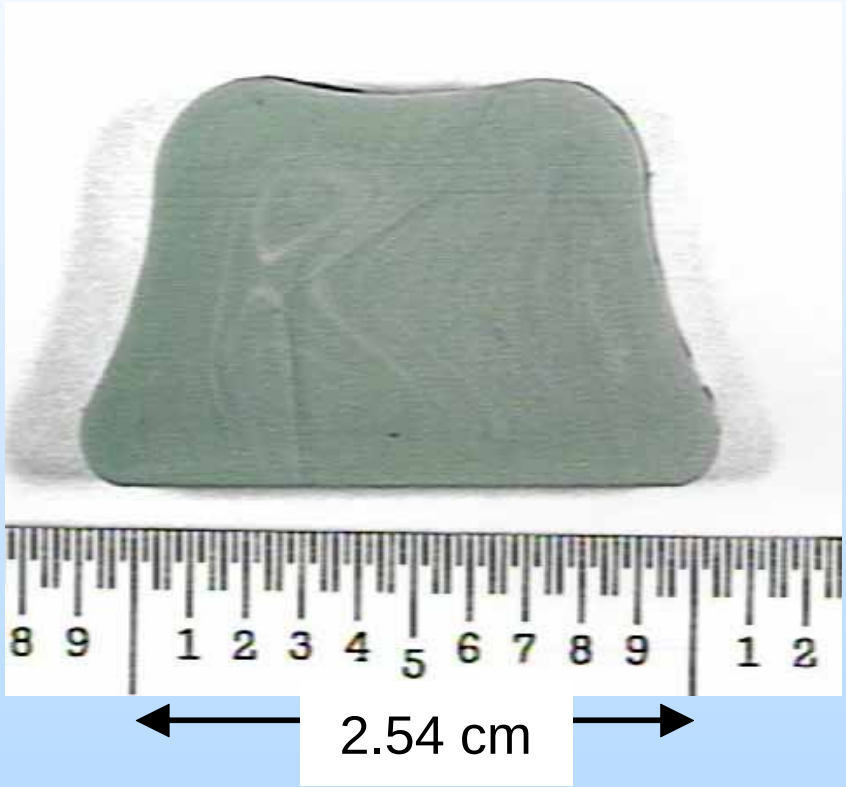
A +0.109 cm in Y
B +0.048 cm in Y
C +0.025 cm in X
D +0.089 cm in X
E + 0.025 cm in X

Overall Height from Pre -cured Skin

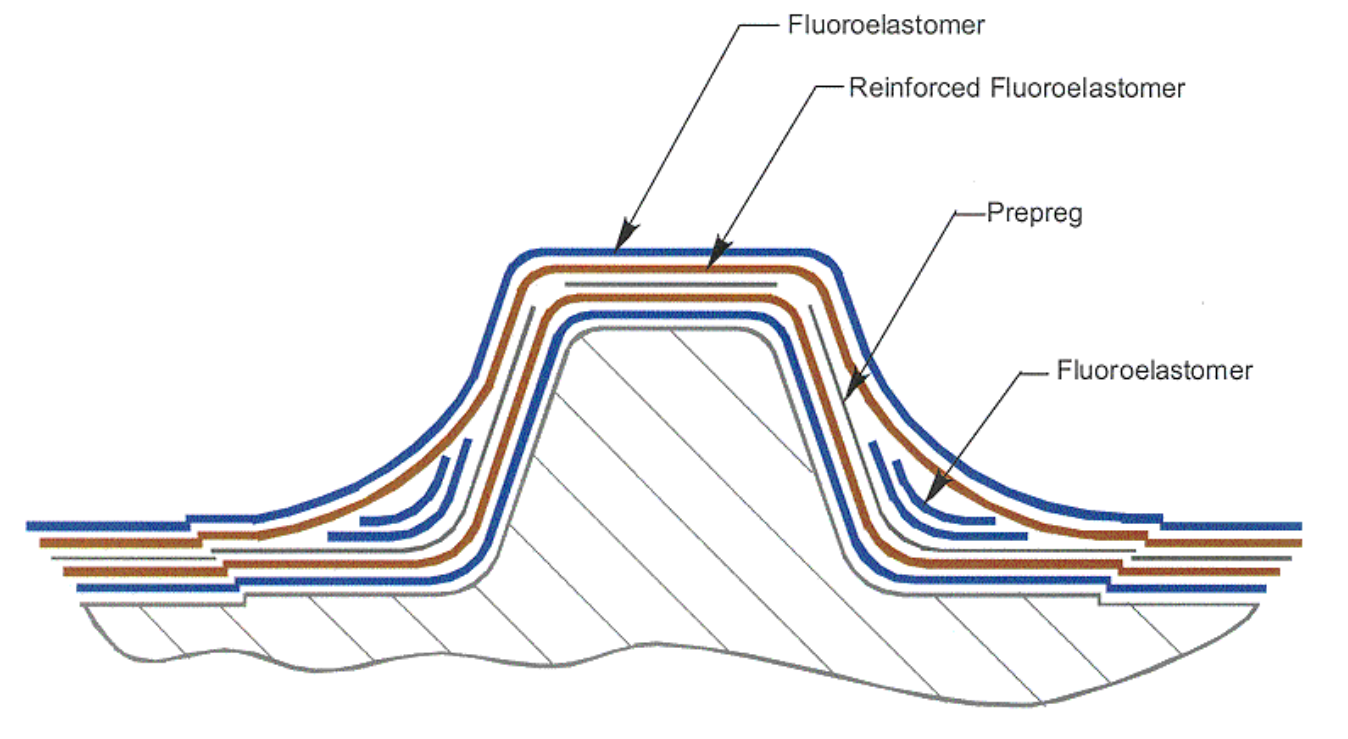
F 2.21 cm

- Compensate mandrel to prevent ballooning

- **First Round Results – Silicone Elastomeric Mandrel with compensated sides and top**

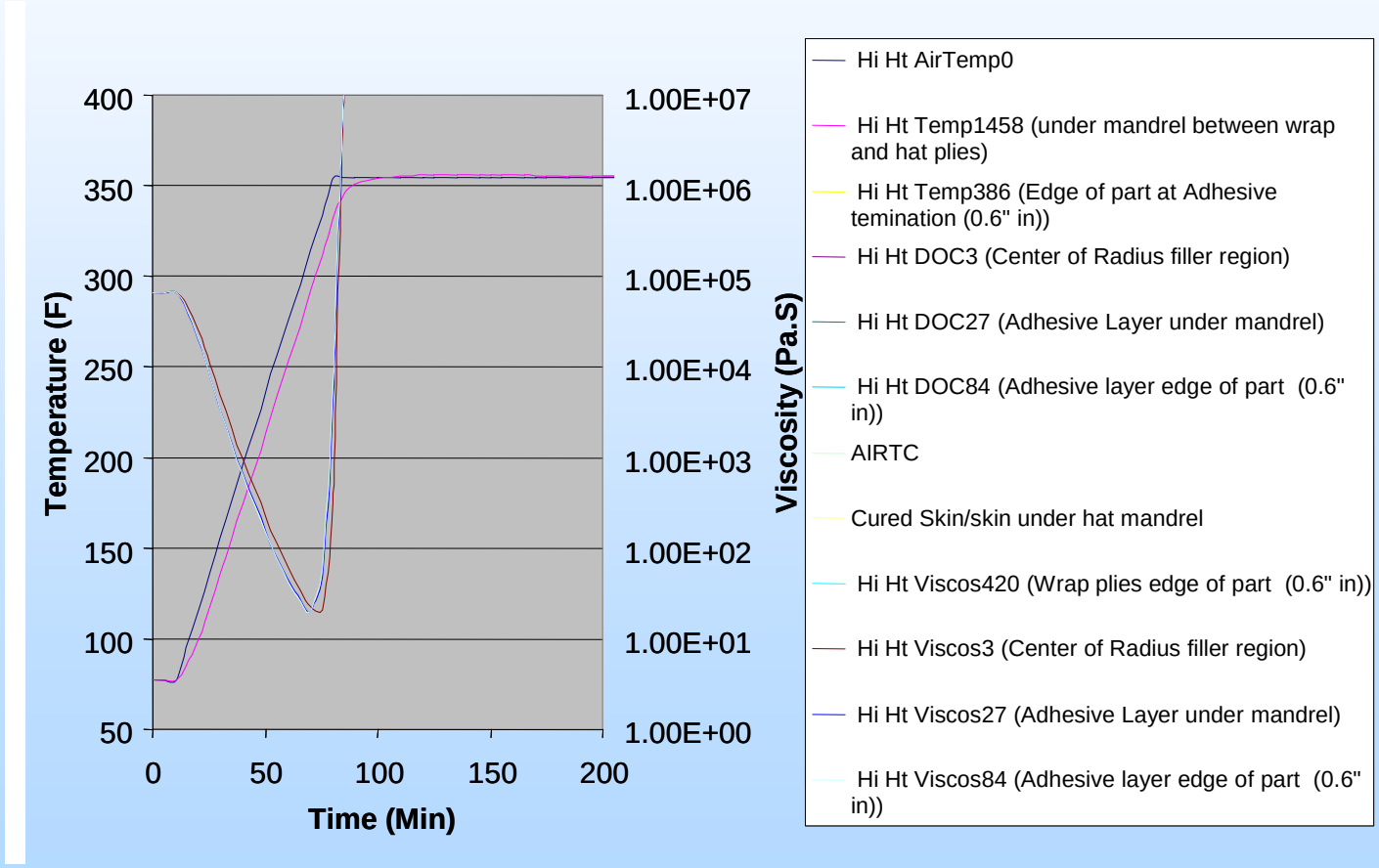


- **Tooling and Processing Approach – Caul sheet**

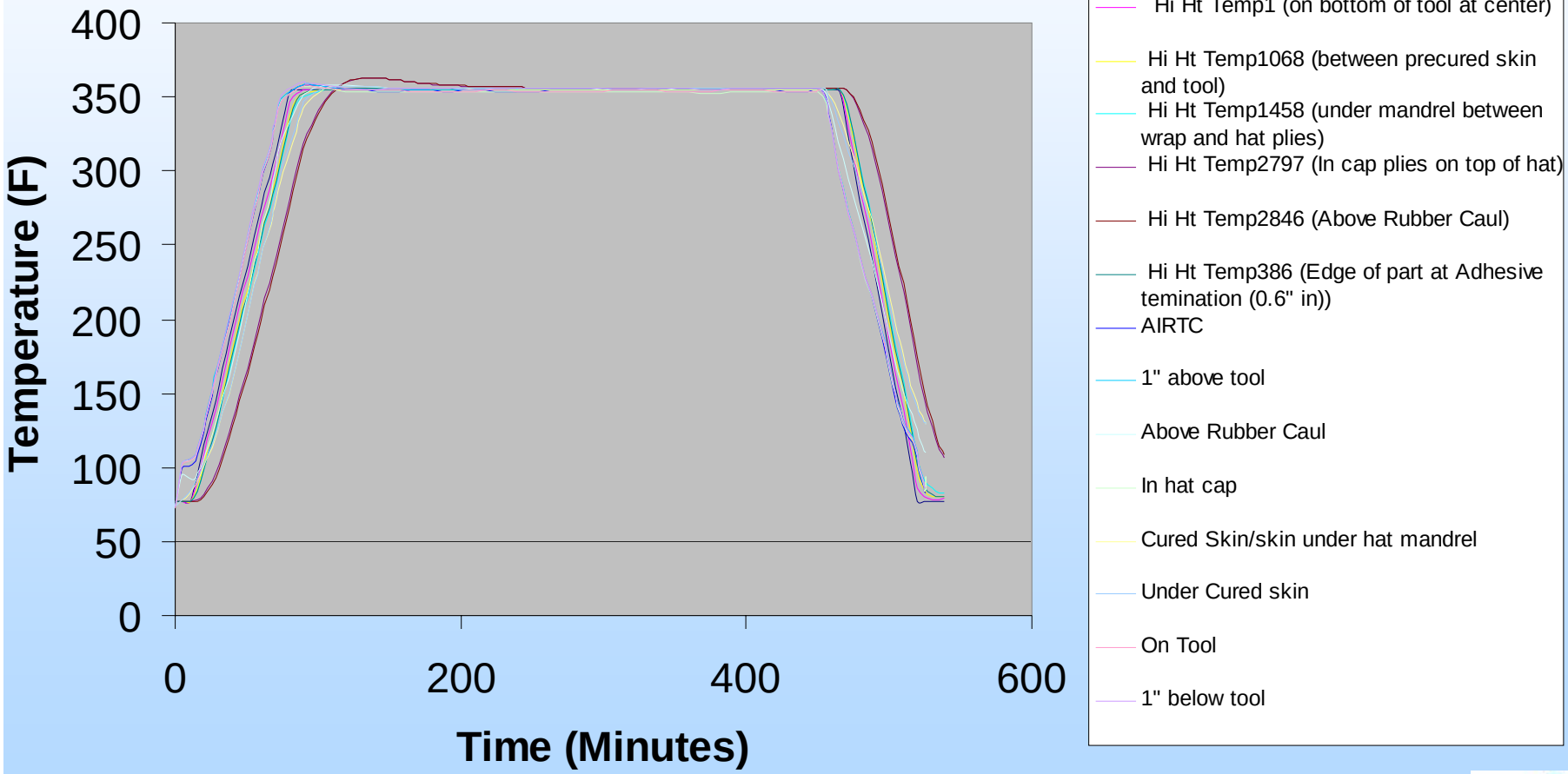


- Use semi rigid reinforcement in caul sheet to maintain radius control

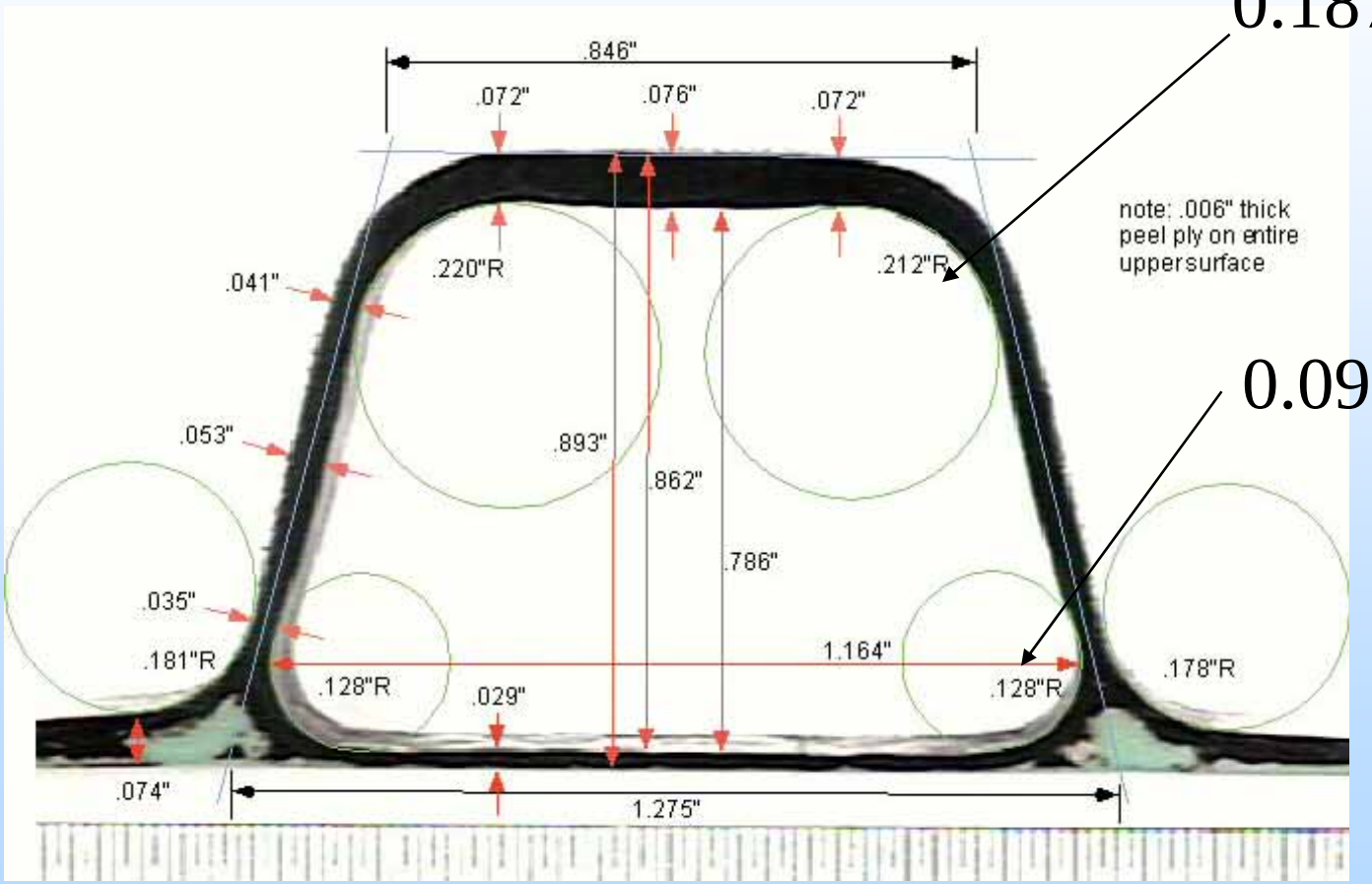
- **First Round Results – Viscosity Predictions**



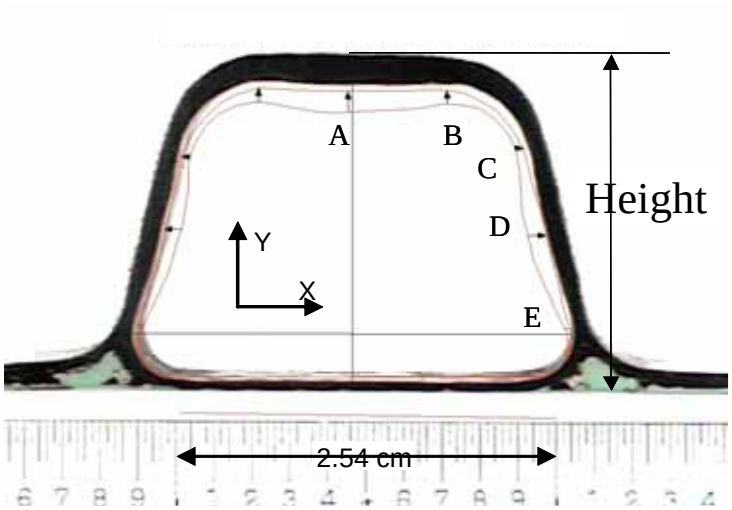
- **First Round Results – Temperature predictions vs. actual**



- **First Round Results**



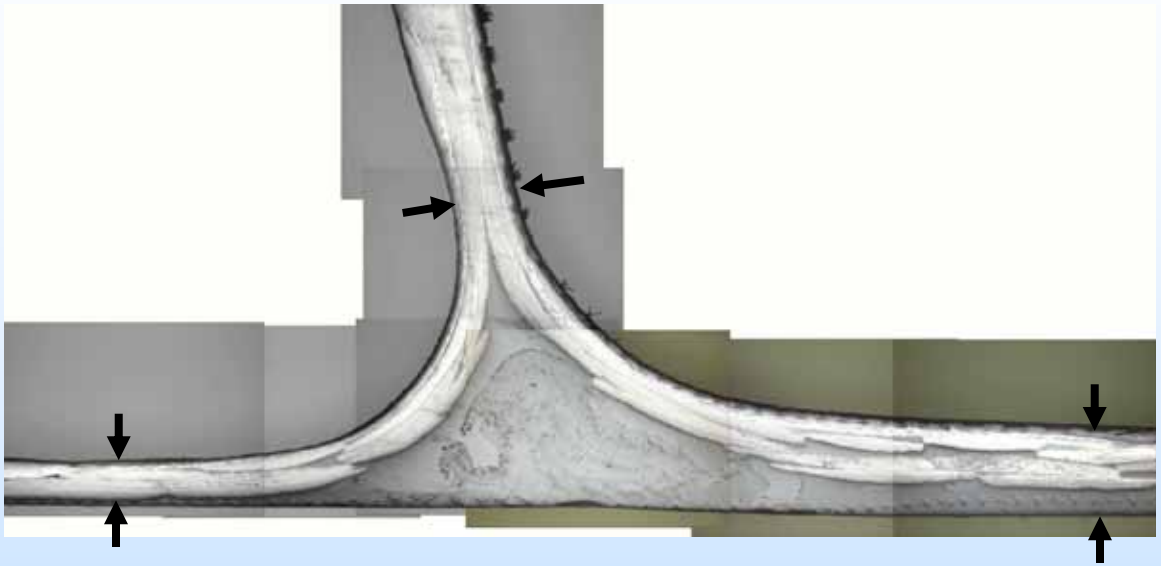
- **First Round Results Shape Predictions vs. Actual**



Mandrel Growth

	Predicted	Measured
A	+0.109 cm in Y	+0.152 cm in Y
B	+0.048 cm in Y	+0.102 cm in Y
C	+0.025 cm in X	+0.076 cm in X
D	+0.089 cm in X	+0.102 cm in X
E	+ 0.025 cm in X	+0.025 cm in X
Height	2.21 cm	2.27 cm

• First Round Results



- Excessive Radius thinning at top of lower radii
- Thickness mismatch between plies under hat and outside hat
- While possibly acceptable additional goal was to match geometry of structural prediction
- Interaction between shape compensated mandrel and semi rigid caul sheet
- Team decided to redesign mandrels to reduce radius thinning

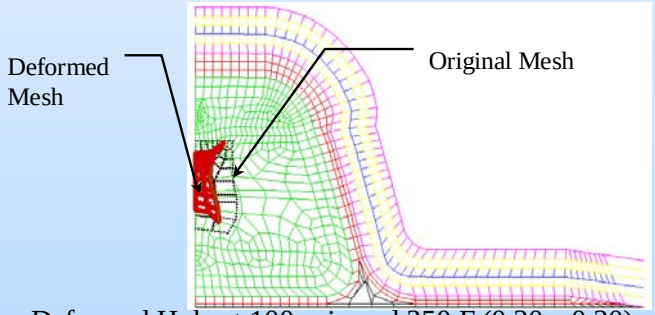
• Second Round

Mandrel Redesign Effort performed using simulation guided design of Mandrel with:

Plane stress design assumption – Expansion in 2D, 3rd dimension extrudes mandrel out ends (experience based)

Plane strain design assumption – Bulk behavior due to friction between mandrel and prepreg (Simulation based)

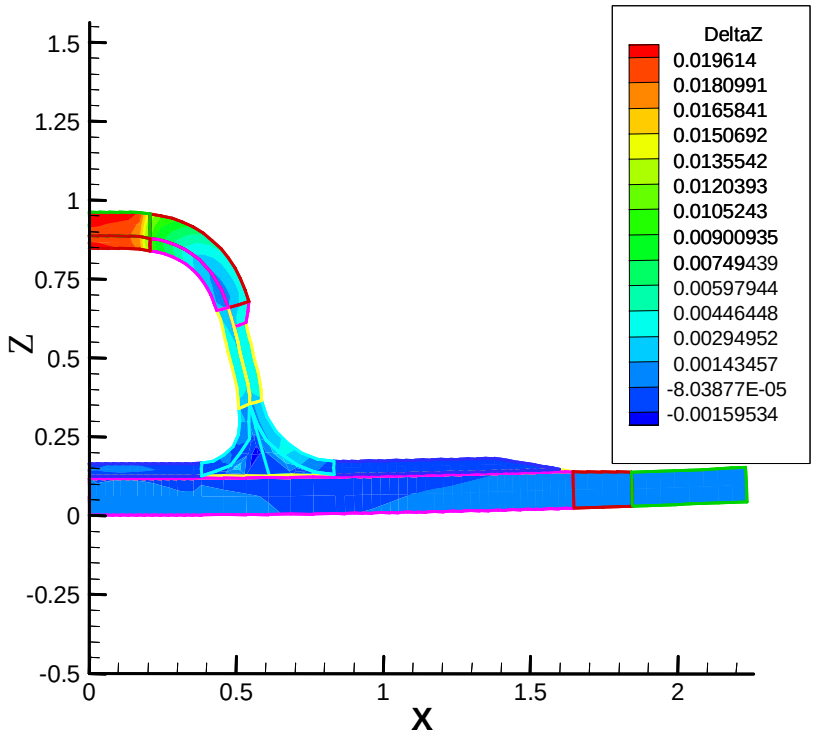
Plain stress with open space to mitigate bulk behavior and help control shape (Simulation based)

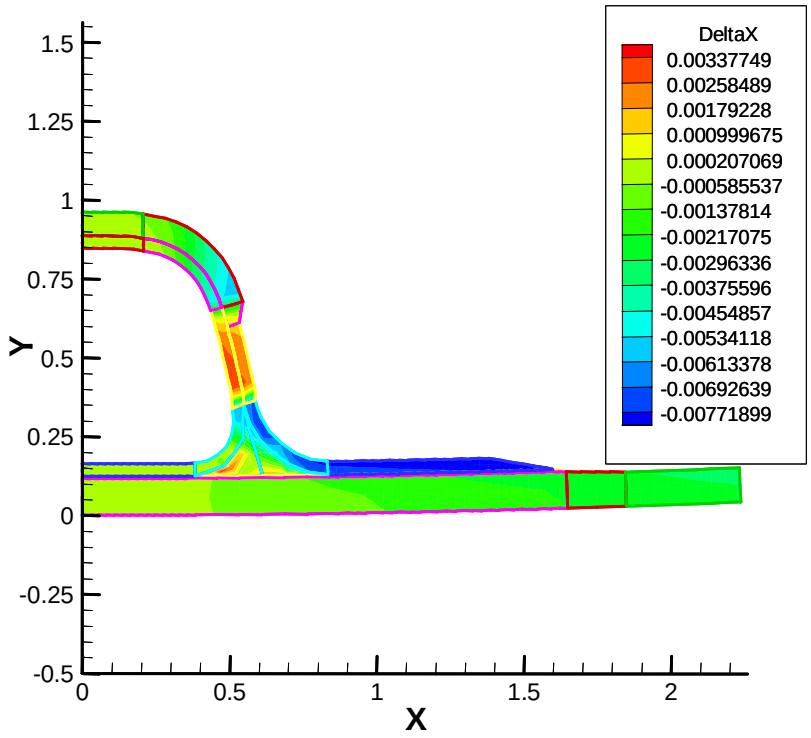


Deformed Hole at 100 psig and 350 F (0.30 x 0.30)

Fabrication trials performed with all three designs to reduce schedule risk

- **Second Round Results**





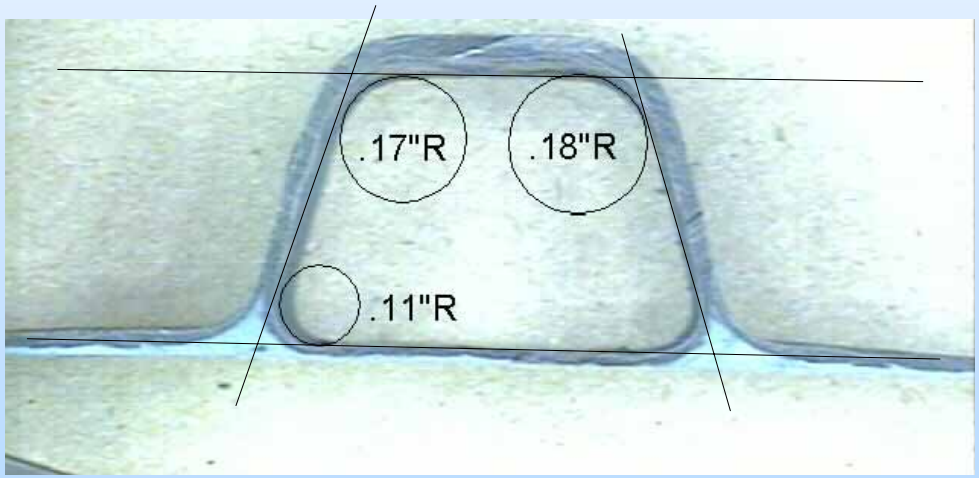
- Updated simulation without mandrel compensation and rigid caul sheet

- **Second Round Results**

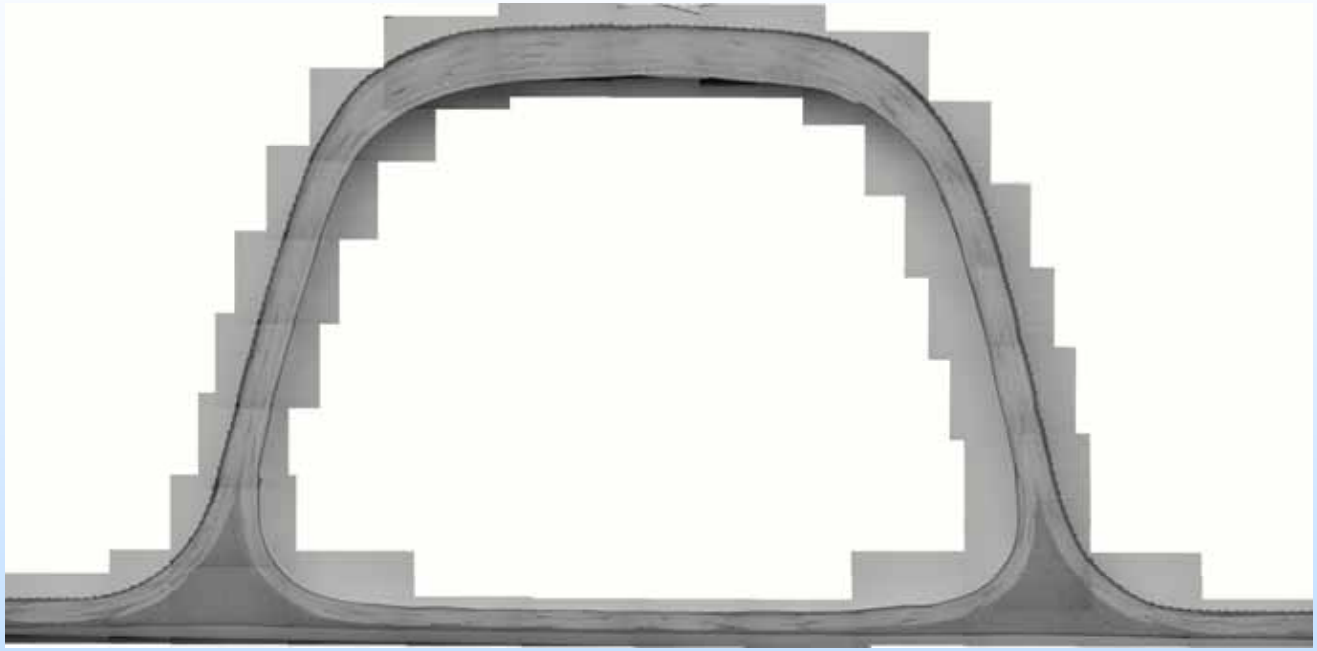
Spec #	Between Hats (L side)		Under Hat			Between Hats (R side)	
	Mid bay	Radius	L Radius	Center	R Radius	Radius	Midbay
Target	0.040	0.040	0.040	0.040	0.040	0.040	0.040
Plain Strain	0.038	0.042	0.035	0.032	0.042	0.037	0.039
Hole-2	0.040	0.062	0.035	0.037	0.035	0.062	0.042
Hole-1	0.041	0.070	0.032	0.042	0.040	0.067	0.042
Plain Stress-2	0.041	0.050	0.037	0.035	0.040	0.052	0.042
Plain Stress-1	0.041	0.050	0.040	0.035	0.039	0.048	0.036

- **Second Round Results**

Plane Stress assumption designed mandrel provided best results
All radii and thickness within tolerance
Successful fabrication of all parts to date



- **Second Round Results**



Plain Strain Assumption Mandrel Sizing
A little Ballooning but otherwise nailed it on 2nd iteration

• Summary

•Temperature – Thermal response within range of predictions with exception of plies on top of hat. Most probable cure assumptions did prove conservative, All heat up rate and hold times met.

•Viscosity- All areas gelled near or at final hold temperature. Cure cycle modification to increase minimum heat-up rate may be wise to avoid premature adhesive gelation

•Degree of Cure – All parts reached desired degree of cure per simulation, experimental confirmation pending. Pre-cured skin did not advance beyond acceptable DOC range during co-bond.

•Shape – While initial trial offered production type quality parts, deviations from as designed geometry complicated strength prediction efforts. Therefore AIM tools and experience were used to redesign the hat mandrel shape. The second fabrication trial produced a part meeting all tolerance requirements. This successful mandrel design was based on analysis rather than experience. It should be noted that ALL parts fabricated were of typical or better quality for hat stiffened panels.

Acknowledgements

Program Manager - Dr. Leo Christodoulou of DARPA/DSO

NAVAIR Program Monitor – Dr. Ray Meilunas

Boeing Program Managers - Gail Hahn, Karl Nelson (Deputy), and Charley Saff (Deputy)

AIM-C Team – American Optimal Decisions, Boeing (St. Louis, Seattle, Canoga Park, Philadelphia), Convergent Manufacturing Technologies, Cytec Engineered Materials, Intec, Lee and Associates, Massachusetts Institute of Technology, Materials Sciences Corporation, Northrop Grumman Corporation, NSE Composites, Roth Group, Stanford University

Certification Advisory Team – Air Force, Army, Federal Aviation Administration, NASA (Langley), and NAVAIR